UDC 551.509.313:551.501.74:551.524.77:551.557

# Computation of Upper Tropospheric Reference Heights From Winds for Use With Vertical Temperature Profile Observations

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**ABSTRACT**—A method is presented for combining remotely measured temperature soundings and wind data to provide a pressure-height reference level in the upper troposphere. In an initial phase of the study, balanced heights over North America were computed solely from standard wind reports and were found to conform closely to comparable National Meteorological Center height analyses. For oceanic application, height values from processed satellite infrared spectrometer (SIRS) data were objectively analyzed to obtain a geostrophic wind field. This wind field was used as a first guess in analyzing winds reported by commercial aircraft. The various terms of the balance equation were computed from the gridpoint winds, and balanced heights were determined by relaxation. These balanced heights blend temperature profile observations and wind data. They were used as upper level reference heights, and SIRS thickness values were subtracted from them to obtain height fields in the lower troposphere. Some typical results are illustrated.

## 1. INTRODUCTION

The satellite infrared spectrometer (SIRS) instruments flown on the Nimbus 3 and 4 satellites measure the radiance emitted by the atmosphere in the 15 $\mu$m $CO_2$ band in seven narrow spectral intervals that pertain to seven altitude layers (Wark and Fleming 1966, Wark and Hilleary 1969). These radiances, together with a water vapor window radiance, can be used to obtain a profile of atmospheric temperature as a function of pressure. This has opened a new avenue for obtaining information for objective analysis and numerical prediction over vast regions of the earth. The processing of the SIRS A data from Nimbus 3 has been described by Smith et al. (1970). Using statistical methods, they were able to recover temperature profiles of acceptable accuracy when compared with radiosonde observations. In addition, in extratropical regions, it was found feasible to relate the radiances statistically to the heights of pressure surfaces. A different method was developed by Smith et al. (1972) to process temperature profiles from SIRS B data taken by Nimbus 4. The method is an iterative one that uses National Meteorological Center (NMC) temperatures as a first guess. They found that the pressure-height information was acceptable only if an accurate reference value was available from another source. A reference height at 850 mb was used for SIRS B data. However, the reference value does not need to be near the earth's surface. In the present study, we have computed "balanced height" fields at 250 or 300 mb for use as upper tropospheric reference values. A primary data source, in addition to SIRS observations, is comprised of aircraft reports of winds in the 30,000- to 40,000-ft layer. Over large regions of the midlatitude oceans, these wind measurements from commercial aircraft are numerous and provide a good sampling of the synoptic scale flow patterns. In the future, winds from other measuring systems, such as constant-level balloons tracked by satellites (Lally 1967, Solot and Angell 1969), can be used in computing balanced heights if they become sufficiently numerous. Other atmospheric motion data, for example, cloud motions determined from geosynchronous satellite observations, may also prove amenable to the same treatment.

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## 2. APPROACH

Over the oceans, observations from the SIRS B instrument are much more numerous than those from weather ships. We found that analyses of temperature, height, and geostrophic winds made from SIRS data depict the larger scale meteorological features of the troposphere reasonably well. Winds measured by Doppler or inertial navigation systems on commercial airliners comprise an additional source of information. These reports are quite numerous along certain oceanic routes; however, they contain considerable noise and, therefore, require special editing (described later). The SIRS geostrophic winds may be used as first-guess fields in analyzing the aircraft winds. From the gridpoint wind analyses, the nondivergent winds and associated quantities such as relative vorticity can be computed. Next, the balance equation can be solved to give the geostrophic wind vectors that conform to the nondivergent winds. From these balanced geostrophic winds, the associated balanced pressure-height field can be determined by relaxation. This balanced height field will differ from the SIRS height field primarily to the extent that the aircraft winds differ from the SIRS geostrophic winds. The SIRS data and aircraft winds combined in this manner may be expected to give a relatively accurate and detailed wind analysis in the upper troposphere over large portions of the oceans of the Northern Hemisphere. If so, it follows that the balanced height field will be reasonably accurate and can serve as a reference level in using profile data; that is, the SIRS thickness values can be added to or subtracted from the upper reference heights to obtain height analyses at higher or lower altitudes.

The following steps were carried out for several typical cases:

1. Rawinsonde data for the United States were used to compare balanced heights, computed solely from 250-mb winds, with NMC operational height analyses at the 250-mb level. These comparisons showed that the balanced heights from winds conformed very closely to the NMC heights in a region of relatively dense and accurate data.
2. Gridpoint analyses were made of aircraft winds over the North Atlantic and North Pacific Oceans, after the winds had been edited by an objective routine. In these analyses, initial-guess fields in the form of geostrophic winds from SIRS data were used.
3. Nondivergent winds were computed from the gridpoint winds, and from these a set of geostrophic winds was computed to conform to the balance equation. From these geostrophic winds, pressure heights were computed by relaxation.
4. The balanced height fields were compared to other height analyses, including the NMC operational height analysis and an analysis based on SIRS height data alone.
5. From the 250-mb (or 300-mb) balanced height fields and an analysis of SIRS thickness values, 850-mb (or 1000-mb) height fields for the Atlantic and Pacific Oceans were computed. These were compared with NMC analyses for the same levels.

## 3. DATA AND OBJECTIVE ANALYSIS

Magnetic tapes in the "B–3" format of NMC contain rawinsonde data from land stations and ships, aircraft reports, processed SIRS temperature and height data at mandatory pressure levels, "bogus" data and numerous NMC operational analyses of height and temperature. Observations by the SIRS A instrument on Nimbus 3 are made about every 8 s along the orbital track; these are sampled and a sounding is provided approximately every 2.5° of latitude. The separation between orbital tracks has been shown by Smith et al. (1970). The SIRS B instrument on Nimbus 4 has a scanning pattern and obtains observations to the sides of the orbital path; naturally, this greater coverage facilitates accurate analysis. Radiances are not obtained from levels beneath cloud layers; thus, lower tropospheric conditions are not sampled by these instruments at approximately one-fifth of the total number of SIRS data points contained on the magnetic tapes.

The aircraft winds have special characteristics that require treatment not needed when analyzing rawins. They tend to cluster along major oceanic air routes, and, therefore, some averaging of nearby reports is performed. At present, a sizable number of aircraft winds, on the order of 5 percent, contain errors in location, wind direction, or wind speed. In most cases, such errors can be detected by comparing the reports with neighboring ones or with other data or analyses. An objective method for doing this is described by Mancuso (1972).

The wind measurements are made at varying heights (300–200 mb) and times ($\pm$ 6 hr of analysis). Therefore, they must be adjusted to apply to the height and time of the analysis (250 or 300 mb and either 0000 or 1200 GMT). The height adjustment is made by adding to the measured wind a thermal wind that is derived from an analysis based on SIRS temperature data. When the SIRS measurements are relatively complete, this provides an excellent means of correcting the wind data. The time adjustment to a wind report is made by advecting it at a fraction of its speed to a new location. The fraction used has been set arbitrarily at 0.5 because 12-hr forecasts of 300-mb wind fields over the United States made in this manner provided results that were significantly superior to persistence (Endlich and Mancuso 1967, Mancuso and Endlich 1969).

The bogus reports of winds and heights are inserted by skilled analysts at NMC to improve the coverage of data and to control the positions of Highs, Lows, troughs, and so forth, in the objective analyses. The analysts also consider qualitative synoptic aids, quasi-objective information based on satellite pictures, and flow patterns deduced from aircraft winds.

The objective analysis method used in this study is an outgrowth of one used earlier (Endlich and Mancuso 1968) and is analogous to that in use at NMC (Cressman 1959). A gridpoint value of the variable of interest is computed as a least-squares fit to several of the nearest observations. The observations are weighted inversely with distance. A special feature of the technique is that upstream or downstream observations are given greater weight than cross-stream observations at equal distances from the gridpoint. This gives an elliptic field of weights with the long axis in the local direction of flow. Inman (1970) has also used this type of anisotropic weighting, and Sasaki (1971) has analyzed it from a theoretical standpoint. First-guess fields can be introduced with prescribed weights and are significant in areas of few observations but are of lesser influence where data are dense. Further details concerning objective editing and analysis are given by Mancuso (1972).

## 4. COMPUTATION OF NONDIVERGENT WINDS, GEOSTROPHIC WINDS, AND BALANCED HEIGHTS

In this study, we have exercised a preference for performing "direct" or "vector" operations on the wind fields; that is, the nondivergent and irrotational vector fields are obtained from the original gridpoint wind analysis by altering the winds as described by Endlich (1967). Since the irrotational winds and associated divergence often contain a considerable degree of error inherent in the wind data, they are discarded. Geostrophic wind vectors that correspond to the nondivergent winds in accord with the balance equation are then computed in the same iterative manner (Endlich 1968).

Values of balanced height that fit the geostrophic vorticity field are computed by relaxation using an alternating-direction-implicit method developed by Mancuso (1967). This technique uses Neumann boundary conditions; that is, the winds along the boundary are used to specify the normal gradients of height according to the geostrophic relationship. The computation is unique except for an additive constant applicable to the whole field. This constant is selected so that the average value of the balanced field will be the same as a desired average; for example, the average value of SIRS height data or of NMC heights. This procedure gives a means for computing balanced height fields entirely from winds, except that the average balanced height value is adjusted in an appropriate manner.

## 5. EXAMPLES OF BALANCED HEIGHTS COMPUTED FROM WINDS

The question of the accuracy with which balanced heights can be computed using wind data alone was investigated using rawinsonde reports at the 250-mb level. The balanced heights from these winds were compared with NMC heights to judge their reliability. Although NMC heights are not an absolute standard of reference, they provide a convenient, high-quality field for comparison. The area of comparison was chosen as the United States since both the wind and height data there are as error free and as densely located as in any area of comparable size on earth, so that the incidental differences in such a comparison will be small.

A gridpoint wind vector analysis using only the wind reports (without a first-guess field) was made on a 3° latitude-longitude spherical mesh. (For the area of interest, this mesh contains approximately the same number of points as the NMC mesh.) From these gridpoint winds, the nondivergent wind vectors were computed. The vorticity, Jacobian, and other terms of the balance equation were calculated from the nondivergent winds. Using this information, the geostrophic wind vectors that conform to the nondivergent winds were computed. Then a height field was fitted to the geostrophic winds by relaxation. This balanced 250-mb height field was adjusted so that its mean value would conform to the average height value determined for the same area by a separate analysis of radiosonde heights. This latter value usually differed by only 5–10 m from the mean of the NMC heights but was as large as 20 m in one case.

Figure 1 shows the 250-mb winds over the United States at 1200 GMT on Nov. 16, 1970. The associated geostrophic wind vectors are illustrated in figure 2, and the balanced heights, in figure 3. To facilitate comparison of balanced heights and NMC heights, we transformed the original NMC heights, which pertain to a polar sterographic grid, onto our spherical grid by use of the objective analysis routine. The resulting NMC height field, which is slightly smoothed compared to the original, is shown in figure 4.

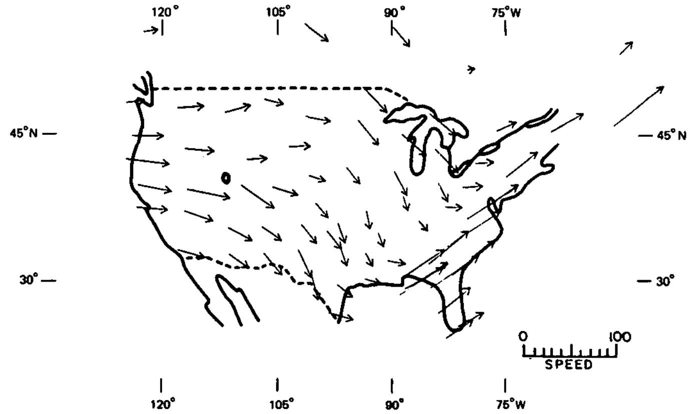


FIGURE 1.—Winds (m/s) at the 250-mb level over the United States measured by rawinsonde at 1200 GMT, Nov. 16, 1970.

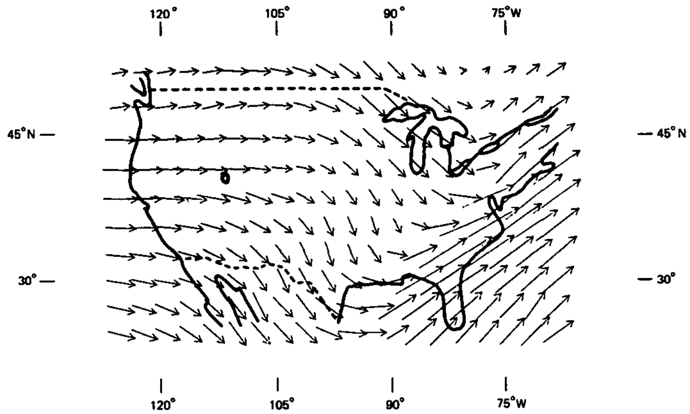


FIGURE 2.—Geostrophic wind vectors at 250 mb computed from the observed winds. Time same as figure 1.

The differences between figures 3 and 4 are largest at the southeastern and southwestern boundaries where there are no wind reports. Since we wished to test the accuracy of the balanced heights against NMC heights only within the area of dense data coverage, we focused on the region bounded by 30° and 45°N, 75° and 120°W. For this region (containing 96 gridpoints), the correlation between the balanced and NMC heights is 0.99, and their root-mean-square (rms) difference is 29 m. Correcting this rms difference for the difference in the average values of the two fields, we obtain a residual rms difference of 21 m in the patterns. If one notes that the rms error of measuring height at the 250-mb level is approximately 20 m (Lenhard 1970), the level of disagreement between the balanced heights from winds and NMC heights appears to be small.

A similar analysis for 1200 GMT on Nov. 27, 1970 (not shown), gave a correlation with NMC heights of 0.99 and an rms difference (including a small difference in their average values) of 22 m. For a summer situation (1200 GMT on July 19, 1970), the correlation found between the two fields was 0.98, and the rms difference was 16 m. Similar results were obtained using data for Jan. 15, and July 17 and 18, 1970.

In summary, these analyses over the United States strongly support the concept of using wind data as a means

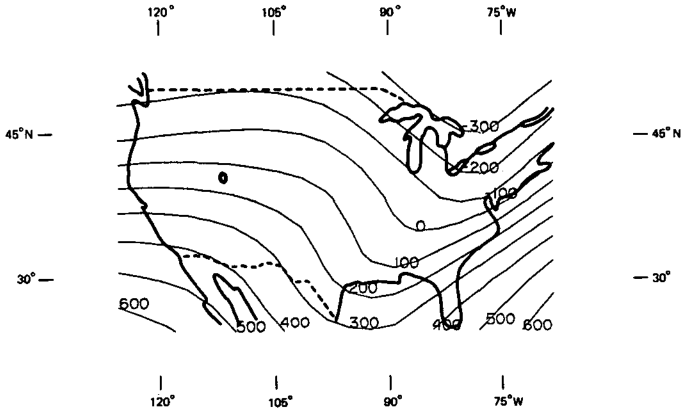


FIGURE 3.—Balanced heights at 250 mb computed by relaxation to fit the geostrophic wind vectors. Time same as figure 1.

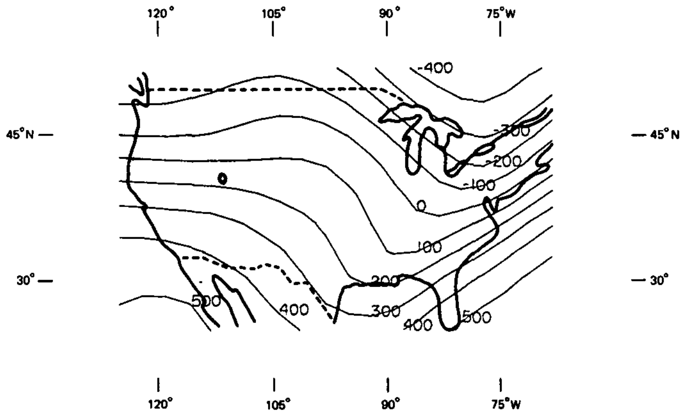


FIGURE 4.—NMC height analysis at 250 mb for comparison with figure 3.

of obtaining a height field in such regions as the oceans where wind reports are much more numerous than height observations.

## 6. CASE STUDIES OF SIRS DATA

### North Pacific Ocean, November 16, 1970

This case had very strong flow in the upper troposphere as shown by the edited aircraft winds of figure 5. The locations of SIRS data points are represented by the letter S in figure 6. The distribution of points is good over the southern portion of the region but rather sparse in the northern part, due presumably to widespread cloud layers. Checkmarks without labels represent data from land or ship stations around the periphery of the area. In addition, the letter B denotes so-called bogus reports of 300-mb height and wind as taken from the B–3 tape; these were mentioned in section 3.

An analysis of the 300-mb SIRS and radiosonde heights (not including bogus data) and the associated geostrophic winds is shown in figure 7. The uneveness of the field is due largely to gaps in the data. The average value of the height field over the grid is computed and saved for later use. No previous data or analyses were used as first-guess fields in this series of charts. The geostrophic wind vectors

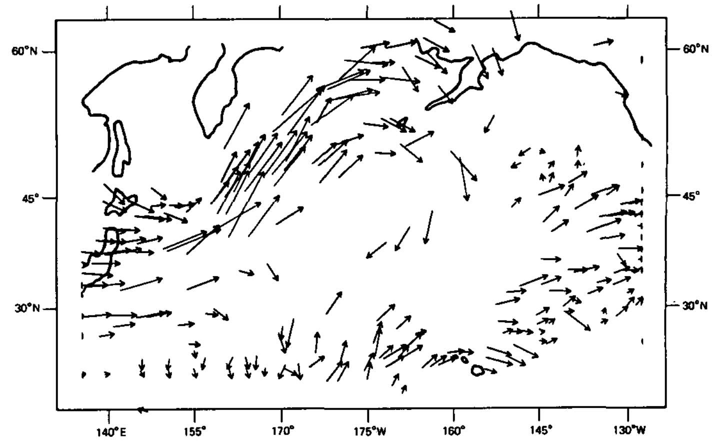


FIGURE 5.—Winds reported by commercial aircraft between 0800 and 1600 GMT, Nov. 16, 1970, in the 30,000- to 40,000-ft altitude layer over the North Pacific Ocean, after objective editing.

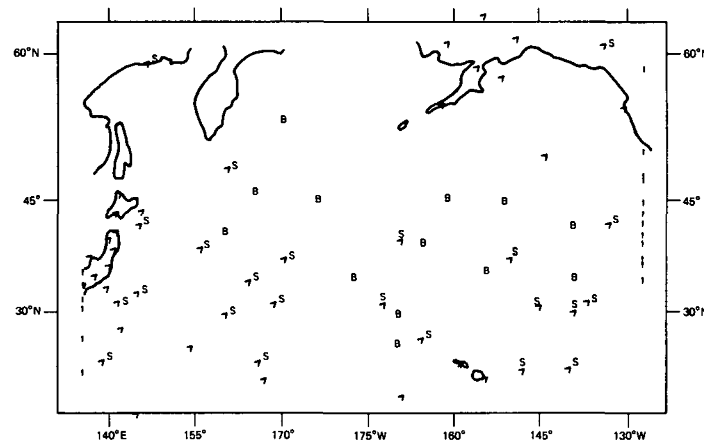


FIGURE 6.—Locations of data in the North Pacific on Nov. 16, 1970. S denotes SIRS data points, a plain check denotes a land or ship radiosonde, and B denotes "bogus" data.

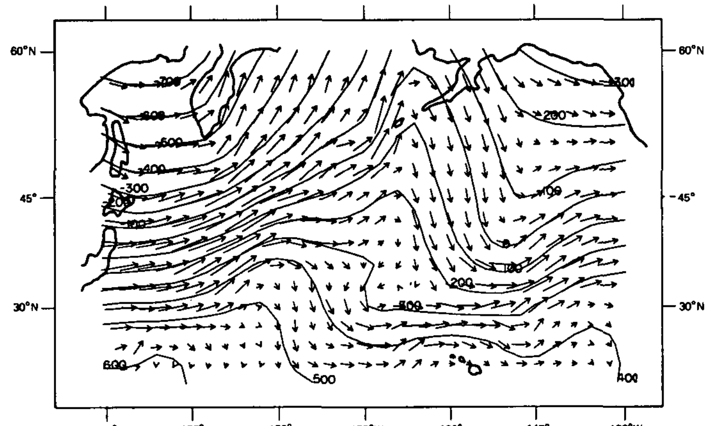


FIGURE 7.—The 300-mb height field and geostrophic winds at 1200 GMT on Nov. 16, 1970, determined from SIRS and radiosonde data.

of figure 7 were used as a first guess in analyzing the winds of figure 5. Figure 8 shows the resulting analysis. Weighting factors in the objective analysis routine were set to accomplish a smoothing that tends to suppress random

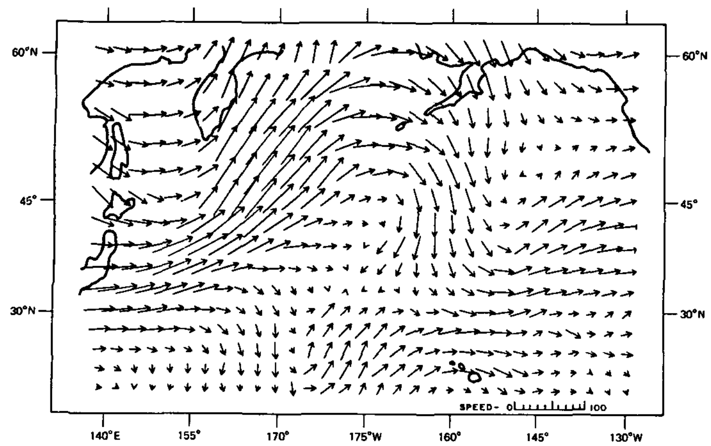


FIGURE 8.—Gridpoint analysis of the winds (m/s) of figure 5 made using the geostrophic winds of figure 7 as the initial estimate at 1200 GMT, Nov. 16, 1970.

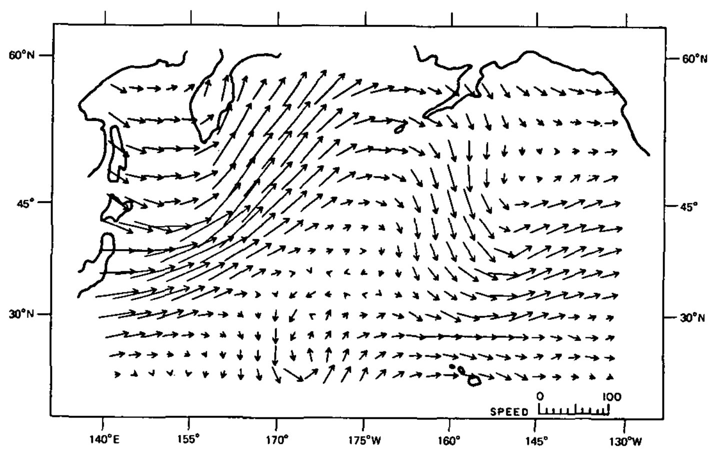


FIGURE 9.—Geostrophic wind vectors (m/s) at 300 mb computed from figure 8.

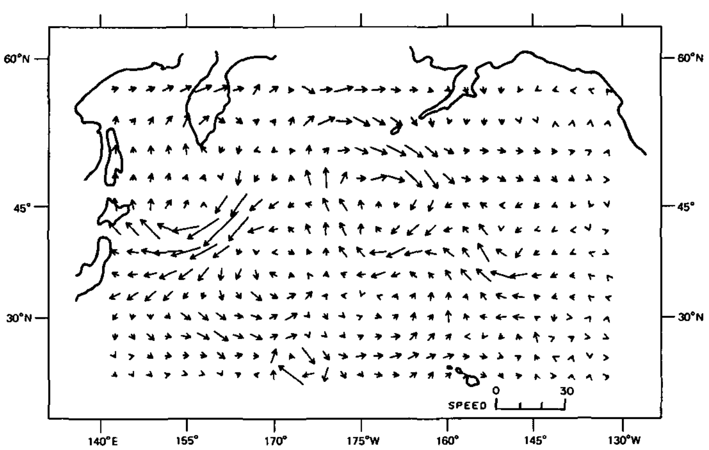


FIGURE 10.—Geostrophic departure vectors (m/s) computed from figure 8. (Note that the length scale is expanded by a factor of 3.)

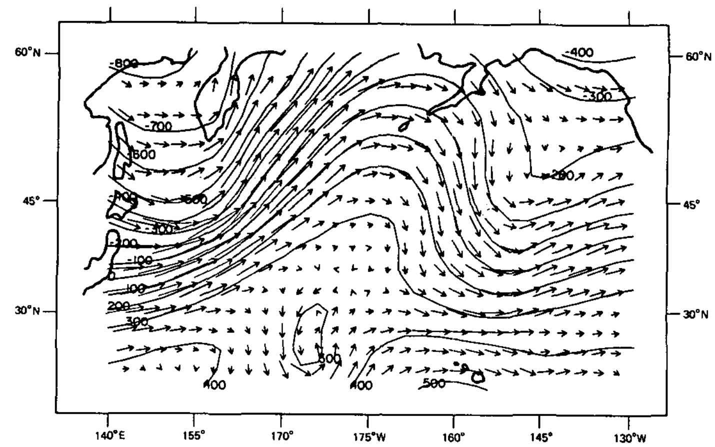


FIGURE 11.—Balanced heights at 300 mb based on aircraft wind reports and SIRS heights. The geostrophic wind vectors shown are the same as in figure 9.

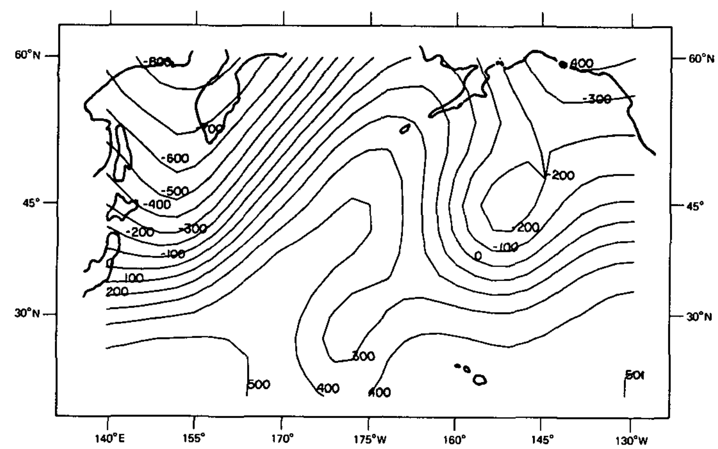


FIGURE 12.—NMC 300-mb height analysis at 1200 GMT, Nov. 16, 1970, for comparison with figure 11.

uncertainties in the aircraft wind reports. The nondivergent winds were computed from figure 8 by the direct method. Since they are very similar in appearance to figure 8, they are not illustrated. The geostrophic wind vectors were then computed, as shown in figure 9, and the geostrophic departures (the difference between nondivergent and geostrophic winds) are shown in figure 10. (Note that the length scale for the departures is three times longer than in the previous charts.) This departure field, which is important in the dynamics of the flow, is based only on SIRS and aircraft data and illustrates the sort of information that can be obtained by using them together.

The geostrophic winds of figure 9 are repeated in figure 11, along with the balanced height field fitted to them by relaxation. The average value of this height field is made to be the same as the average height of figure 7. The NMC height field for the same area is shown in figure 12. The general similarity of figures 11 and 12 is encouraging. Significant differences in synoptic scale features can probably be attributed to the absence of bogus reports in our analysis. For example, the NMC analysis has a cutoff Low at approximately 45°N, 150°W, centered on a bogus report. Similarly, the very strong horizontal gradients in figure 12 centered at 45°N, 165°E may have been produced by bogus heights and winds (four of them having speeds of 80 m/s) in this area.

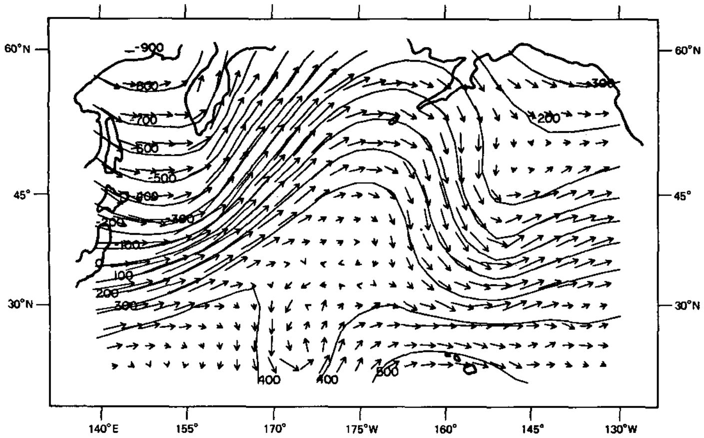


FIGURE 13.—Balanced heights at 300 mb computed using only aircraft wind reports and SIRS thickness data. Time is same as in figure 12.

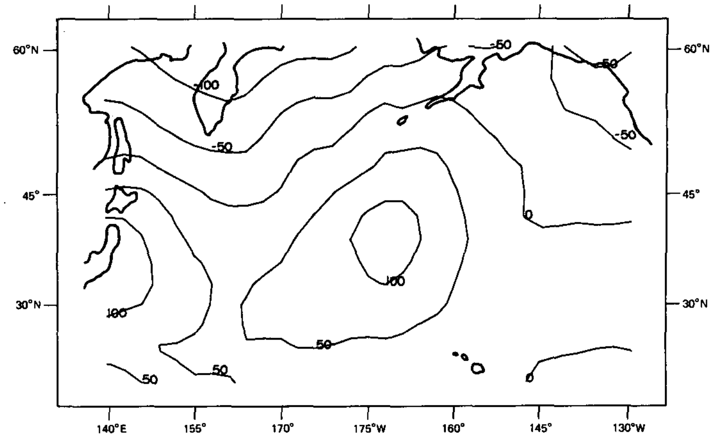


FIGURE 14.—Height analysis at 1000 mb computed from the balanced 300-mb heights of figure 11 and a thickness field determined from SIRS and radiosonde data. (No surface data were used.)

A similar analysis at 300 mb can be made without using the SIRS statistical height values. Instead, one can use the SIRS 1000- to 300-mb thickness (dependent solely on the SIRS temperature profile) as an estimate of the 300-mb height field (Smith 1971). This is tantamount to assuming that the 1000-mb height field is flat with a "D" value of zero everywhere. However, in the strongly baroclinic atmosphere, this assumption gives surprisingly reasonable results. The main difficulty concerning the thickness field on this particular day is that there are insufficient data, particularly over the northwestern Pacific Ocean, so the thickness pattern there is not reliable. This is not very important in making an analysis of the aircraft winds, but it is of crucial importance if the thickness field is subtracted from upper level heights to obtain a height analysis in the lower troposphere, as discussed later. The balanced heights computed using only SIRS thickness data and aircraft winds are shown in figure 13. It has less horizontal detail and weaker gradients than does figure 11.

A height field at 1000 mb was obtained by subtracting the SIRS 1000- to 300-mb thickness analysis from the 300-mb balanced heights of figure 11. As mentioned earlier, the thickness field in this particular case is somewhat uncertain over the northwestern Pacific Ocean because of a scarcity of SIRS data there. The resulting 1000-mb height field had gradients in this region that appeared to be too strong. Therefore, the thickness field was altered to make it conform in shape to the balanced 300-mb height field. Using this altered thickness, we obtained the 1000-mb height field of figure 14. In comparison with the NMC 1000-mb height field (fig. 15), the gradients of figure 14 are too weak. In other cases (described later), the agreement between our lower tropospheric analyses and those of NMC is much better. We believe that in the present case there are insufficient SIRS data to define the thickness pattern adequately over part of the area.

These analyses illustrate several points. The present SIRS height data can be used to give an upper tropospheric height analysis over oceans that appears to be fairly reliable on a synoptic scale, except where SIRS data are sparse. (Such areas are generally covered by extensive, thick cloud systems.) A similar statement applies to the analysis of SIRS thickness data. The SIRS height analysis in the upper troposphere can be improved considerably in regard to detailed features (such as locations of jet streams, troughs, and ridges) by use of the relatively numerous wind reports from commercial aircraft that are obtained over portions of the oceans. The balanced heights based on SIRS height and aircraft winds are in good agreement with NMC height analyses except in data-sparse areas. There, the NMC analyses appear to be significantly affected by the use of bogus heights and winds, which we have not used. The accuracy of lower tropospheric height analyses obtained by subtracting SIRS thicknesses from an upper level reference height is critically dependent on the coverage of SIRS reports. The present case was not optimum in regard to SIRS data coverage.

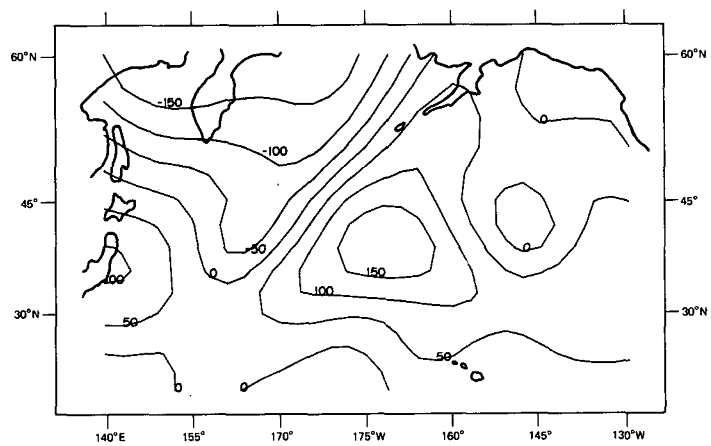


FIGURE 15.—NMC 1000-mb analysis at 1200 GMT, Nov. 16, 1970, for comparison with figure 14.

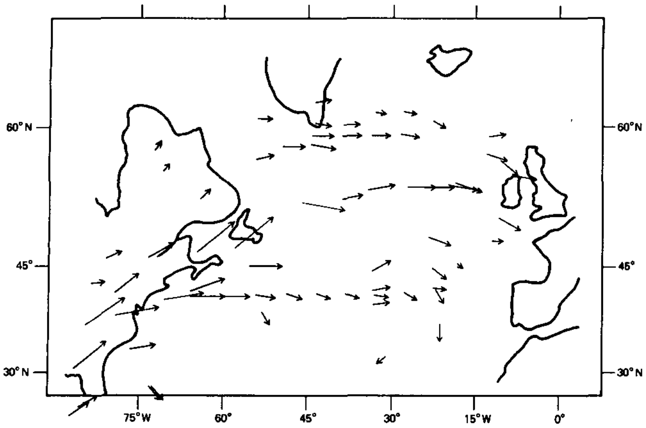


FIGURE 16.—Winds reported by commercial aircraft between 0800 and 1600 GMT, Nov. 16, 1970, in the 30,000- to 40,000-ft altitude layer over the North Atlantic Ocean, after objective editing.

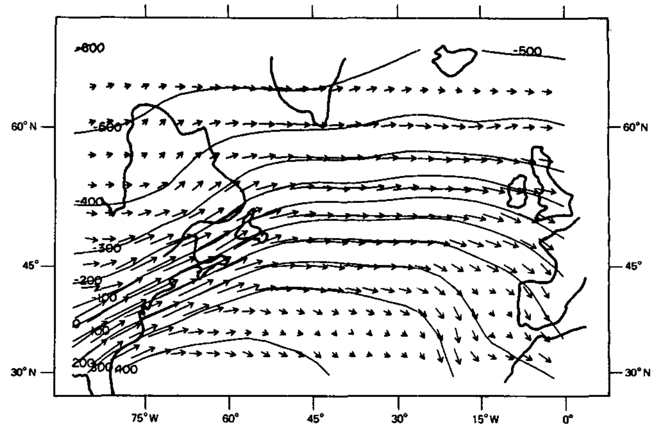


FIGURE 19.—Balanced heights at 250 mb computed using only aircraft winds and SIRS thickness data. Time same as in figure 18.

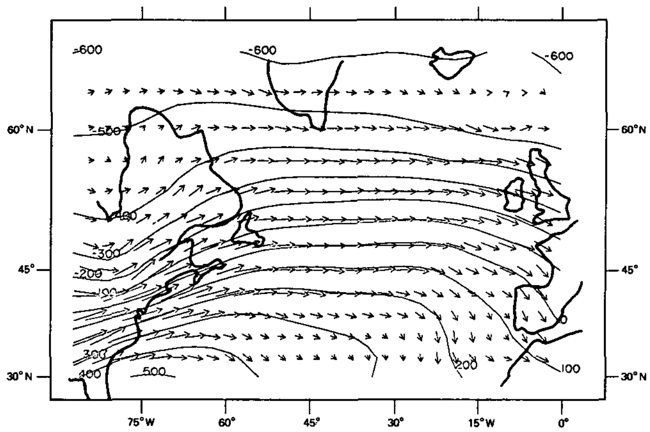


FIGURE 17.—Balanced heights at 250 mb based on aircraft winds and SIRS heights. Time same as in figure 16.

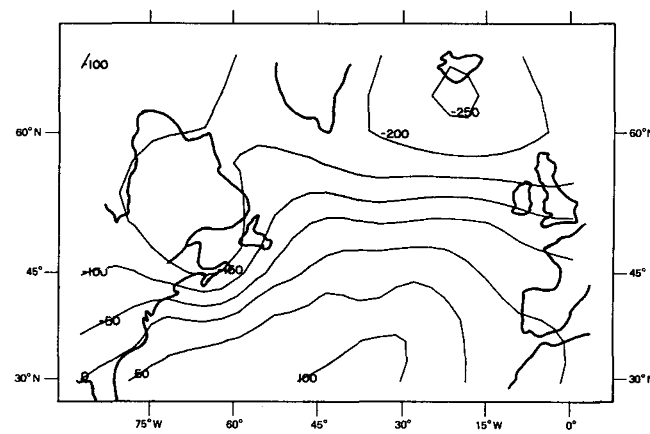


FIGURE 20.—Height analysis at 850 mb computed from the balanced 250-mb heights of figure 17 and a thickness field determined from SIRS data (using an NMC thickness field as the initial estimate).

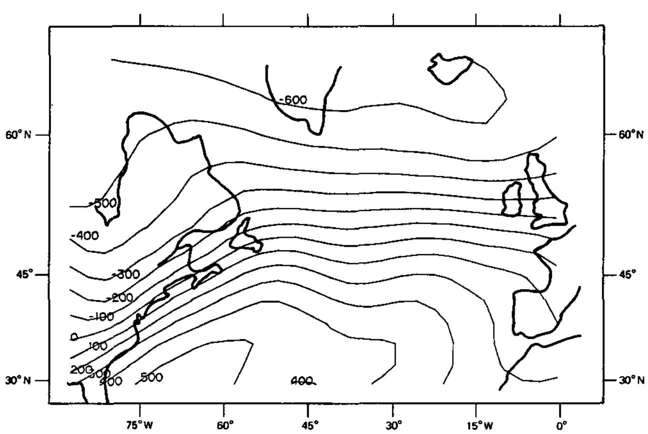


FIGURE 18.—NMC 250-mb height analysis at 1200 GMT, Nov. 16, 1970, for comparison with figure 17.

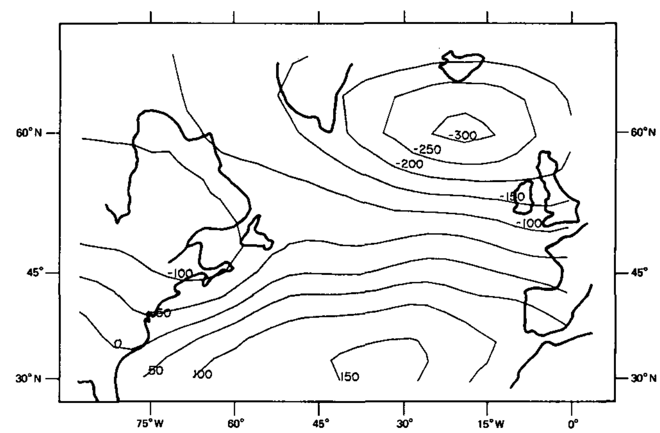


FIGURE 21.—NMC 850-mb height analysis at 1200 GMT, Nov. 16, 1970, for comparison with figure 20.

## North Atlantic Ocean, November 16, 1970, and North Pacific Ocean, July 19, 1970

Analyses were made at the 250- and 850-mb levels using the same procedures described above. The edited aircraft winds in the Atlantic are shown in figure 16. The coverage of SIRS data points was good over the area, and radiosonde data for stations in eastern North America were also included in the analysis. The balanced height field determined from aircraft winds and SIRS data is shown in figure 17. The comparable NMC height field is

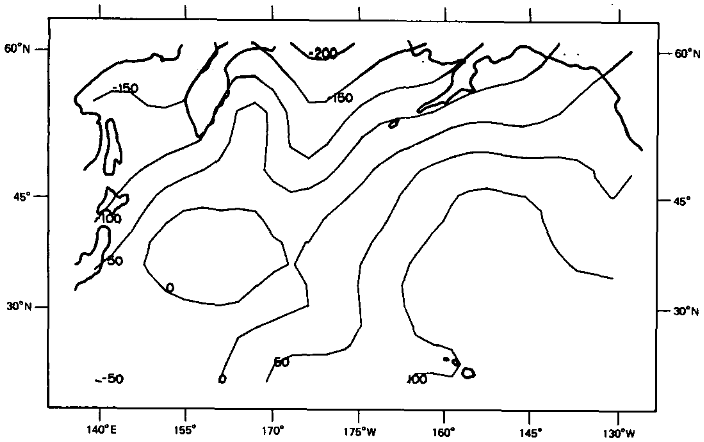


FIGURE 22.—Height analysis at 850 mb computed from balanced 250-mb heights and a thickness field based on SIRS data. Time is 1200 GMT, July 19, 1970.

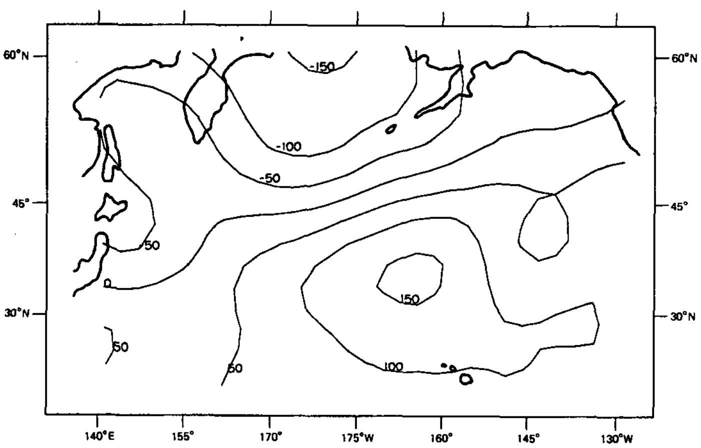


FIGURE 23.—NMC 850-mb height analysis at 1200 GMT, July 19, 1970, for comparison with figure 22.

shown in figure 18. (We did not investigate the extent to which this field may have been influenced by bogus data.) A balanced height field computed from aircraft winds and a SIRS thickness analysis is shown in figure 19. The weaker gradients of thickness as compared with height are reflected in this chart, but the general pattern is a reasonable approximation to figure 17.

In analyzing the SIRS thickness field, we used NMC thickness values as initial estimates to control the analysis in areas of relatively sparse reports. The 850-mb chart obtained by subtracting the resulting SIRS thickness field from the balanced 250-mb heights of figure 17 is shown in figure 20, and the associated NMC 850-mb field is shown in figure 21. The latter analysis has a deeper Low in the northeastern corner of the grid.

For this case, balanced heights at 250 mb computed from SIRS reports and aircraft winds are in good agreement with the comparable NMC analysis. On subtracting an analysis of SIRS thickness (made using NMC thickness as a first guess), we obtained an 850-mb chart that shows fairly good general agreement with the NMC analysis. The differences between the latter two charts are probably attributable in part to NMCs use of additional low-level data that we did not include.

In the Pacific Ocean case for July 19, 1970, we will show only the 850-mb chart (fig. 22) computed using an upper reference level and a thickness analysis, and the comparable NMC analysis (fig. 23). In this case, the former appears to have the more sharply defined synoptic scale structure.

## 7. SUMMARY

The computations made using data for the United States show that balanced heights computed solely from standard wind observations are in very good agreement with upper tropospheric NMC heights. Their similarity is sufficiently close that the differences between the heights from winds and the NMC heights can be accounted for mainly by the instrumental uncertainties of measuring heights and winds. This supports the hypothesis that edited aircraft wind data are useful in analyzing upper tropospheric conditions over oceans where other data are sparse.

In 1970, the SIRS data were the second most plentiful set of upper air measurements over the North Atlantic and North Pacific Oceans. The SIRS heights at 250 or 300 mb were used to provide geostrophic winds for application as initial estimates in the analysis of aircraft winds. Also, the SIRS temperatures were used to give a thermal wind for adjusting the aircraft winds to a common analysis level. Another application of the SIRS heights is in determining the average value (or labeling) of the balanced upper level height field.

Comparisons of the upper tropospheric balanced height fields (which are a blend of SIRS and aircraft data) over oceans with NMC analyses show reasonably good agreement; however, the balanced heights are generally somewhat smoother than the NMC analyses. Differences between the two fields may be attributed to the use of bogus data by NMC and to differences in methods of analysis. Lower tropospheric height fields that we obtained by subtracting thickness analyses from the upper level reference heights appear reasonable in cases of even and complete SIRS data coverage. In part, our 850- or 1000-mb analyses probably differ from comparable NMC charts because the latter include other data such as surface ship reports. Using surface data was beyond the scope of the present study.

The significance of this work must be considered with respect to the rapid development of weather satellites. Improved remote sensing instruments and data processing methods are expected to give better coverage and greater accuracy in vertical temperature profiles within a few years. The coverage of aircraft winds will probably change only by minor amounts; however, it is likely that more reliable aircraft wind measurements will be provided by automated systems. Other types of winds, which can be treated like aircraft winds, are anticipated. One new source of wind data over the globe is the constant-level balloon floating in the lower stratosphere and tracked by satellites. Another set of atmospheric motion data can be obtained by processing sequences of photographs to obtain cloud motions. Use of an upper tropospheric reference level, based on combined data from several sources, appears feasible and may prove to be advantageous in objective analysis of data from temperature profile sensors carried by satellites.

## ACKNOWLEDGMENTS

The work at Stanford Research Institute was sponsored by the National Environmental Satellite Service (NESS) under Contract No. 0-35199. William L. Smith of NESS contributed helpful advice and comments.

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[*Received January 31, 1972; revised June 19, 1972*]

UDC 551.576.1:551.515.8(084.1)(766)"1971.07.26"

# PICTURE OF THE MONTH
# An Unusual Arcus Cloud

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At approximately 0555 CST on July 26, 1971, the author observed and photographed the passage of this arcus cloud formation (fig. 1) across Norman, Okla. The synoptic situation for the Oklahoma region associated with the arcus passage indicated that a weak, east-west cold front was progressing slowly south-southeastward through the State (fig. 2). All available evidence indicates that the arcus cloud was caused by the passage of the front. Although thunderstorm activity was reported at the same time well to the north of the front in southern Kansas and extreme northern Oklahoma, there was no evidence of any association of the arcus formation with any thunderstorm or shower activity. In fact, the first thunderstorm activity reported in the Oklahoma City area occurred 6 hr later.

Small-scale wind changes associated with the arcus cloud band in the Norman area were recorded at the National Severe Storms Laboratory (NSSL) of the National Oceanic and Atmospheric Administration. Prior to the approach of the arcus cloud, the early morning winds were from a southeasterly direction at 2–5 kt. At the time of the arcus cloud passage, the wind shifted to the north and for a 2- to 3-min period gusted to 14–16 kt. The wind then rapidly decreased in strength to 5–8 kt and remained fairly steady for over an hour before becoming gusty again as a layer of stratocumulus at 800–900 ft above ground moved in from the north.

Arcus clouds usually form in association with density currents that, in turn, can be produced by thunderstorm outflow or frontal activity. Several authors (e.g., Simpson 1969, Benjamin 1968) have investigated the mechanisms for formation of density currents. Laboratory and real atmospheric data indicate density currents can form with

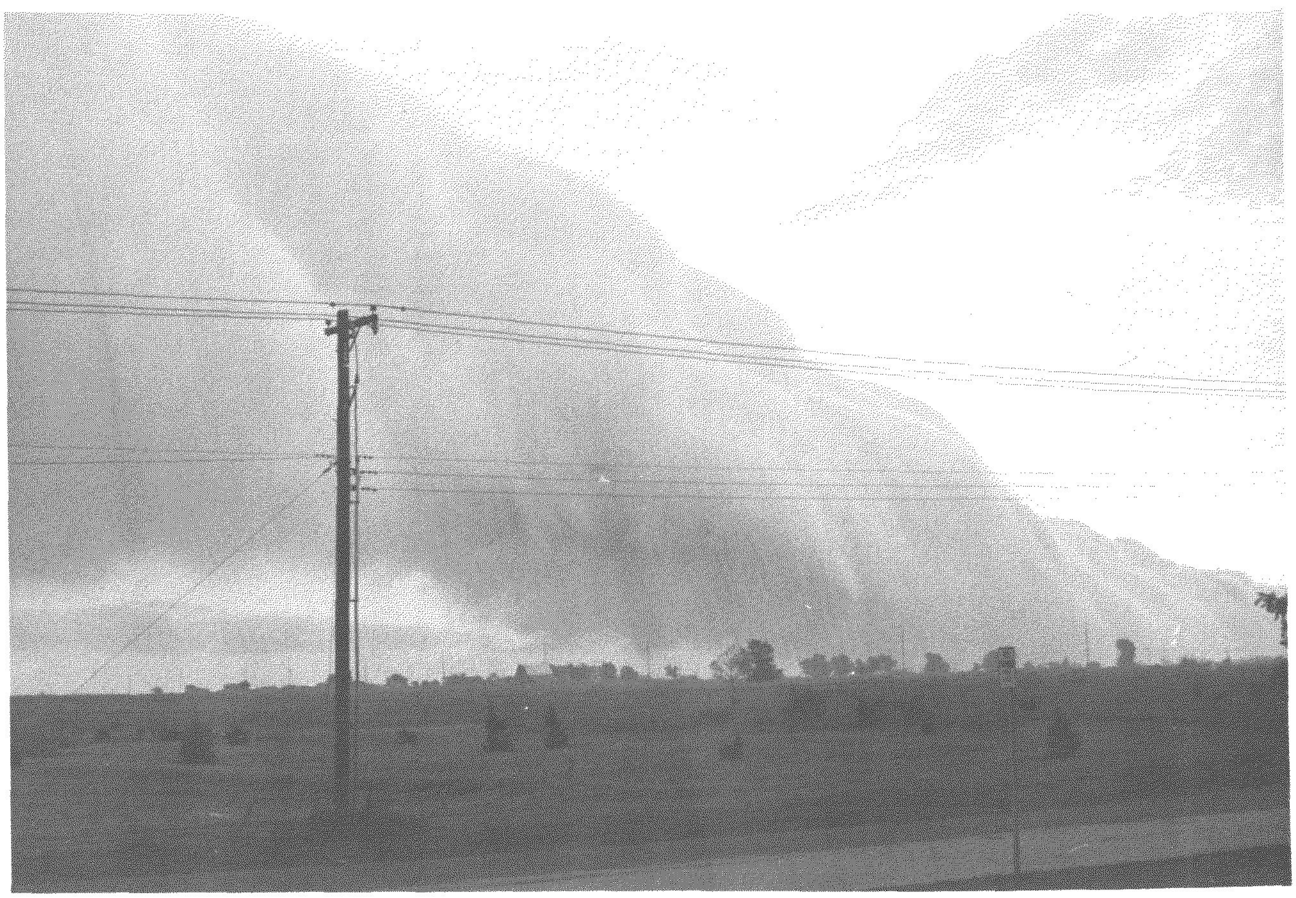

FIGURE 1.—Arcus cloud observed over Norman, Okla., at 0555 CST, July 26, 1971.

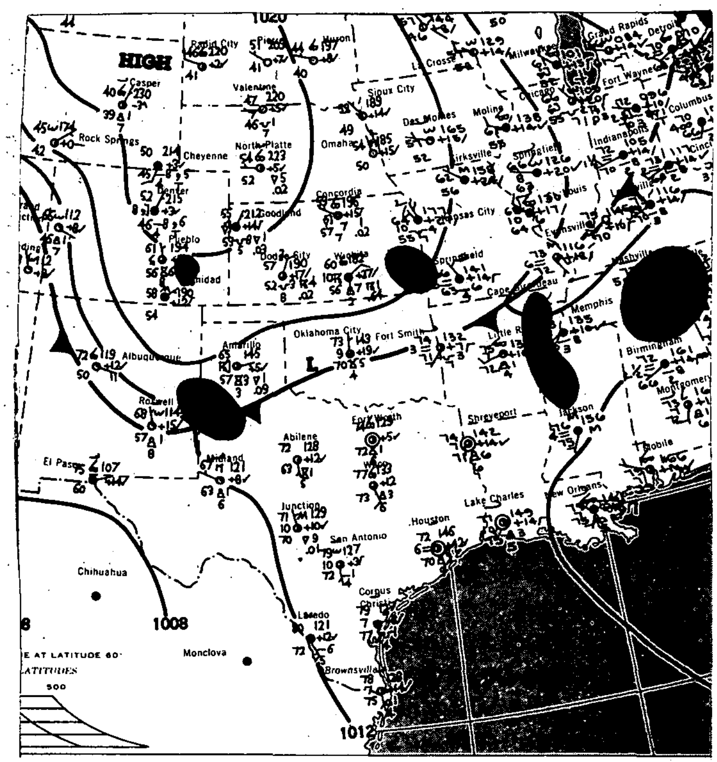


FIGURE 2.—Surface chart for 1200 GMT (0600 CST), July 26, 1971.

a density contrast of only 1 or 2 percent, with the more dense fluid undercutting the less dense fluid.

Atmospheric density currents are sometimes made visible by an abundance of dust or haze. In this situation, large dust storms that outline the area of the cooler, more turbulent air may form (e.g., Stewart 1945, p. 445). At other times, when the atmosphere is quite moist, the interface of the density current may become evident by formation of the arcus cloud. Usually the cloud forms in association with thunderstorm outflow as depicted by Roberts (1972, pp. 550–551).

The arcus formation shown here, however, is somewhat unusual in the respect that it formed at the interface of a density current created by frontal activity rather than that with the more common thunderstorm outflow cited above. Also note that the cloud is characterized by unusually smooth undulations and protuberances associated with the smaller scale turbulent circulations as contrasted with the more pronounced and well-defined turbulent irregularities frequently associated with the leading edge of a dust storm type of density current.

## ACKNOWLEDGMENTS

Acknowledgment is given to S. Barnes and E. Brandes, NSSL, for providing information and data available to them. Additional acknowledgment is extended to G. Darkow for his review and suggestions on this note.

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